

Roadway roughness profile identification from vehicle acceleration by means of dynamic regularized least square minimization

Soichiro Hasegawa¹, Chul-Woo Kim² and Naoki Kawada³.

¹ Ph.D. Candidate, Departure of Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan.

hasegawasouichirou00@gmail.com

² Professor, Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan.

kim.chulwoo.5u@kyoto-u.ac.jp

³ West Nippon Expressway, Engineering Kansai Co., Ltd, Osaka, Japan

Abstract. This study aims to propose a roadway roughness profile identification using the acceleration responses of a vehicle by means of a dynamic regularized least square minimization (DRLS). The DRLS is a method comprising the least square minimization whose cost function is the error between simulated and measured accelerations, a regularization technique to reduce the ill-posedness in the inverse problem, and dynamic programming in the numerical solution. The optimum hyperparameter in the regularization technique can be obtained automatically utilizing the L-curve method, which is a great advantage of the proposed method. The validity of the proposed method is verified via a field experiment on a highway using a test vehicle equipped with accelerometers. The identification accuracy when the vehicle runs at high speed is investigated by comparing it with the roadway roughness measured by laser displacement sensors. The experimental result shows that the proposed method has enough accuracy.

Keywords: dynamic regularized least square minimization, field experiment, roadway roughness, vehicle vibration.

1 Introduction

In the maintenance of roads and bridges, roadway surface roughness is one of the most important parameters affecting not only driving comfort but also pavement and bridge health condition, because a rough roadway surface amplifies the vibration of the bridge when vehicles travel on them ¹⁾. One of the most basic methods of measuring roadway roughness profile is leveling, which directly measures the distance between the roadway surface and a reference elevation. Despite its accuracy, it is a labor-intensive method. Therefore, inspection vehicles equipped with laser displacement transducers have been developed as an alternative to leveling while maintaining accuracy. However, inspection

vehicles are tailor-made systems, which are often expensive. Therefore, there is a need to develop road surface roughness profiling methods that meet the needs for accuracy, labor, and cost. Inspection vehicles equipped with laser displacement transducers ensure labor savings. The inspection method of obtaining information on roadways or bridges by installing sensors on vehicles rather than on bridges is called "drive-by inspection" and has been widely studied ²⁾ - ¹²⁾. Accelerometers are relatively inexpensive and can be easily mounted on any vehicle, so cost savings can be achieved by using accelerometers instead of specialized inspection vehicles fitted with laser displacement transducers. However, in terms of maintaining accuracy, using accelerometers is still a challenge as the displacement identified from acceleration measurements by solving an inverse problem is easily affected by measurement noise and vehicle modeling errors. Moreover, inverse problems are prone to ill-posedness.

To alleviate the ill-posedness in the inverse problem, a method based on the Dynamic Regularized Least Square minimization method (DRLS) is proposed ¹³⁾, and through a field experiment, the validity of the proposed method was verified at lower vehicle speeds. The DRLS method mitigates the ill-posedness in the inverse problem by applying Tikhonov regularization ¹⁴⁾ to the least square minimization. In the Tikhonov regularization, there is a hyperparameter whose value should be chosen in advance. Hyperparameters usually give a great impact on the accuracy of inverse problems. In the DRLS, the L-curve method ¹⁵⁾ is used to estimate an optimum hyperparameter. Furthermore, the application of the dynamic programming method ¹⁶⁾ reduces the time and error in numerical calculation compared to the batch-processing solution using large-size inverse matrices.

This study intends to investigate the feasibility of the proposed roadway roughness profile identification method at higher speeds through a field experiment. The identification accuracy is discussed using the roadway roughness rank defined by ISO 8608 ¹⁷⁾ and the International Roughness Index (IRI) ¹⁸⁾.

2 Road profile identification algorithm

The proposed roadway surface profile identification method named Dynamic Regularized Least Square minimization (DRLS) is briefly introduced in this chapter. In the existing research ^{9), 19)}, the moving force identification (MFI) algorithm is utilized to identify roadway roughness profiles from the moving forces of the vehicle. The proposed method is intended to directly identify roadway roughness profiles from vehicle vibrations, i.e. the state-space equation in the MFI algorithm is revised to enable the direct identification of roadway profile.

Considering a vehicle model idealized as a two-degree-of-freedom half-car model shown in Fig. 1, the equation of motion of a moving vehicle is written as Eq. (1).

$$\mathbf{M}_v \ddot{\mathbf{y}}_v + \mathbf{C}_v \dot{\mathbf{y}}_v + \mathbf{K}_v \mathbf{y}_v = \mathbf{f}_v \quad (1)$$

where, $\mathbf{M}_v$, $\mathbf{C}_v$, and $\mathbf{K}_v$ denote matrices of vehicle mass, suspension damping, and suspension stiffness, respectively.

$$\mathbf{f}_v = \mathbf{K}_r \mathbf{r} + \mathbf{C}_r \dot{\mathbf{r}} \quad (2)$$

where $\mathbf{r} (= \{r_1, r_2\}^T)$ denotes a roadway profile vector along the passage of the vehicle. r_1 and r_2 denote the profiles under the front and rear tires, respectively. $\mathbf{K}_r$ and $\mathbf{C}_r$ are given in Eq. (3) and Eq. (4), respectively.

$$\mathbf{K}_r = \begin{bmatrix} K_1 & K_2 \\ D_1 K_1 & -D_2 K_2 \end{bmatrix} \quad (3)$$

$$\mathbf{C}_r = \begin{bmatrix} C_1 & C_2 \\ D_1 C_1 & -D_2 C_2 \end{bmatrix} \quad (4)$$

where, C_i , K_i , and D_i denote the suspension stiffness, suspension damping, and the distance from the center of gravity of the vehicle to the i -th axle. $i=1$ and $i=2$ indicate front and rear axles, respectively. The equation of motion in Eq. (1) can be rewritten as a continuous-time state-space equation¹⁹⁾. Solving the continuous-time state-space equation as a first-order differential equation gives a discrete-time state-space equation as shown in Eq. (5).

$$\mathbf{X}_{j+1} = \mathbf{M}_e \mathbf{X}_j + \mathbf{G}_e \mathbf{f}_{v,j} \quad (5)$$

where, a state vector $\mathbf{X}_j$ is defined as Eq. (6), and $\mathbf{M}_e$ and $\mathbf{G}_e$ are calculated as Eq. (7) and Eq. (8), respectively. $\mathbf{M}_e$ is an exponential matrix calculated by Pade approximation²⁰⁾.

$$\mathbf{X}_j = \begin{bmatrix} \mathbf{y}_{v,j} \\ \dot{\mathbf{y}}_{v,j} \end{bmatrix} \quad (6)$$

$$\mathbf{M}_e = e^{\mathbf{A}_e h} \quad (7)$$

$$\mathbf{G}_e = \left(\mathbf{A}_e^{-1} (\mathbf{M}_e - \mathbf{I}) \right) \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_v^{-1} \end{bmatrix} \quad (8)$$

$\mathbf{A}_e$ is defined as Eq. (9).

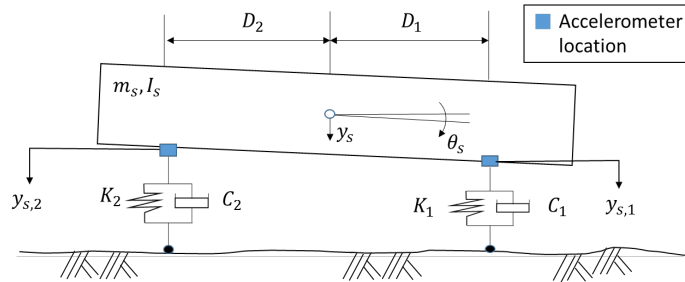


Fig. 1. Two-degree-of-freedom half-car model.

$$\mathbf{A}_e = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}_v^{-1}\mathbf{K}_v & -\mathbf{M}_v^{-1}\mathbf{C}_v \end{bmatrix} \quad (9)$$

Substituting Eq. (2) to Eq. (5), a new discrete-time state-space equation whose external input term is roadway profile is obtained. In this process, the relationship between $\dot{\mathbf{r}}_j$ and $\mathbf{r}_j$ is assumed as Eq. (10).

$$\dot{\mathbf{r}}_j = (\mathbf{r}_{j+1} - \mathbf{r}_j)/\Delta t \quad (10)$$

where Δt denotes a time step. Defining a new state vector as Eq. (11), the new discrete-time state-space equation is obtained as Eq. (12).

$$\hat{\mathbf{X}}_j = [\mathbf{X}_j^T \quad \mathbf{r}_j^T \quad \mathbf{r}_{j+1}^T]^T \quad (11)$$

$$\hat{\mathbf{X}}_{j+1} = \begin{bmatrix} \mathbf{M}_e & \mathbf{G}_1 & \mathbf{G}_2 \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \hat{\mathbf{X}}_j + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{I} \end{bmatrix} \mathbf{r}_{j+2} \quad (12)$$

where, $\mathbf{G}_1$ and $\mathbf{G}_2$ are defined in Eq. (13) and Eq. (14), respectively.

$$\mathbf{G}_1 = \mathbf{G}_e(\mathbf{K}_r - \mathbf{C}_r/\Delta t) \quad (13)$$

$$\mathbf{G}_2 = \mathbf{G}_e \mathbf{C}_r/\Delta t \quad (14)$$

The newly defined discrete-time state-space equation shown in Eq. (12) can easily facilitate the dynamic programming algorithm for direct roadway profile identification. Defining a discrete-time acceleration of the vehicle as $\ddot{\mathbf{y}}_{v,j}$, which is a measurement vector, the relationship between the vehicle acceleration and a state vector is written as Eq. (15).

$$\ddot{\mathbf{y}}_{v,j} = \mathbf{Q}_0 \hat{\mathbf{X}}_j \quad (15)$$

where $\mathbf{Q}_0$ is calculated as Eq. (16).

$$\mathbf{Q}_0 = \mathbf{M}_v^{-1}[-\mathbf{K}_v \quad -\mathbf{C}_v \quad (\mathbf{K}_r - \mathbf{C}_r/\Delta t) \quad \mathbf{C}_r/\Delta t] \quad (16)$$

Solving Eq. (15) using a cost function in the regularized least square minimization, the roadway roughness profile is directly identified. Tikhonov regularization¹⁴⁾ is applied for robustness in the solution. The optimum regularization parameter in the Tikhonov regularization is obtained by L-curve method¹⁵⁾.

3 Feasibility investigation by the field experiment

3.1 Experimental condition

To verify and validate the proposed method for roadway roughness profile identification, the field experiment using test vehicles equipped with accelerometers was carried out on a highway in Japan. The vehicle used in the experiment is a tailor-made road inspection car with laser displacement transducers and data processing systems and is operated by West Nippon Expressway Engineering Kansai Co., Ltd. A picture of the road inspection car is shown in Fig. 2. The road inspection car is a four-wheeled vehicle, and is equipped with three laser displacement transducers that can measure the roadway roughness profile. For the experiment, four accelerometers were newly installed on the vehicle body near each wheel of the road inspection car so as to identify roadway roughness profiles from the accelerations (referred to as "acceleration-identified profile") and compare them with those measured from laser displacement transducers (referred to as "laser-measured profile"). The accelerometers were M-A522AC1 by Seiko Epson Corporation. Since the vehicle is assumed as a two-degree-of-freedom half-car model, the vertical accelerations measured at the two front/rear locations on each side of the vehicle were converted to the accelerations in bounce and pitch directions, and used as inputs



Fig. 2. Picture of road inspection car

Table 1. Model properties of road inspection car

Properties	Value	
Distance between front and rear axles (m)	3.43	
Mass (kg)	Front	3887
	Rear	2178
	Total	6065
Moment of inertia ($\text{kg} \cdot \text{m}^2$)	27354	
Suspension stiffness (N/m)	Front	1053365
	Rear	1047285
Suspension damping ($\text{N} \cdot \text{s/m}$)	Front	17239
	Rear	7370
Natural frequency in bounce motion (Hz)	Front	2.62
	Rear	3.49

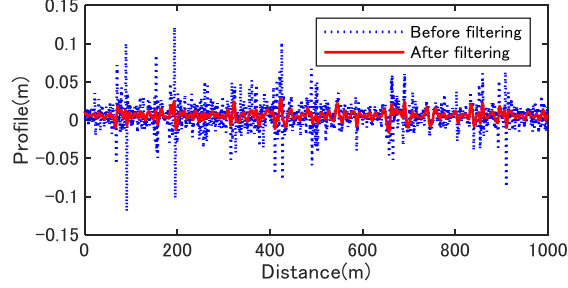


Fig. 3. Laser-measured profiles before and after bandpass filter application.

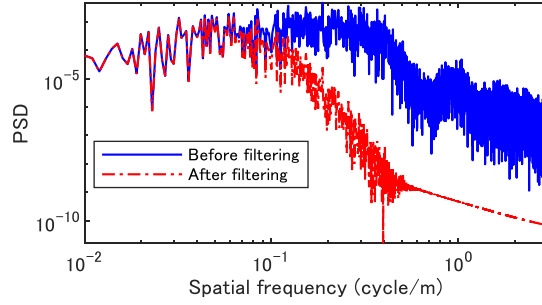


Fig. 4. PSDs of laser-measured profiles before and after bandpass filter application.

for roadway roughness profile identification. The running speed of the vehicle is approximately 70km/h.

Vehicle properties of the road inspection car are summarized in Table 1, and are used as inputs for the roadway roughness profile identification. The axle weights were estimated based on the vehicle inspection certificate and the loads on the vehicle, while the natural frequency was estimated from the power spectral density (PSD) peak of the acceleration measured in the preliminary vibration experiment. The suspension stiffness was estimated from the obtained axle weights and natural frequencies. The damping ratio was estimated from the acceleration waveforms of the preliminary vibration experiment, and the suspension damping coefficient was calculated using the obtained damping ratio, axle weights, and suspension stiffness. The moment of inertia was estimated from the size and mass of the vehicle.

It is noted that the laser-measured profile is measured near the center axis of the vehicle, while the acceleration-identified profile is a profile along the passage under right or left wheels, which are different trajectories. Since the laser-measured profile contains a lot of noise in the higher frequency band, a low-pass filter with a cut-off frequency of 0.1 cycle/m is applied to the roadway roughness profile. Laser-measured profiles and their PSDs before and after applying the low-pass filter are shown in Fig. 3 and Fig. 4, respectively. A bandpass filter with upper and lower cut-off frequencies of 0.03 cycles/m to 0.8 cycles/m is applied to the acceleration-identified profiles. The filtered acceleration-identified profiles are compared with the laser-measured profiles. The

cut-off frequencies were set considering the bandwidth that contributes significantly to IRI²¹⁾.

3.2 Identified profile and PSD

An example of the comparison of the acceleration-identified and laser-measured profiles is shown in Fig. 5. For the comparison in the frequency domain, PSDs of those roadway roughness profiles in Fig. 5 are obtained and are shown in Fig. 6. The degree of roughness of the roadway is classified as class A to class H reading the PSD at the reference spatial frequency (0.1 cycle/m) following ISO 8608¹⁷⁾. Class A is the smoothest roadway, and class H is the poorest roadway. The seven straight lines drawn in Fig. 6 represent the upper limit of each road class. In Fig. 6, PSD values around 0.1 cycle/m are almost in the range of class B for both acceleration-identified and laser-measured profiles. It indicates the identification accuracy is enough in terms of road classification according to ISO 8608.

3.3 Discussion on IRI

The International Roughness Index (IRI) is an index to evaluate roadway roughness in respect of driver comfort, and was proposed by the World Bank¹⁸⁾. The IRI is a ratio of

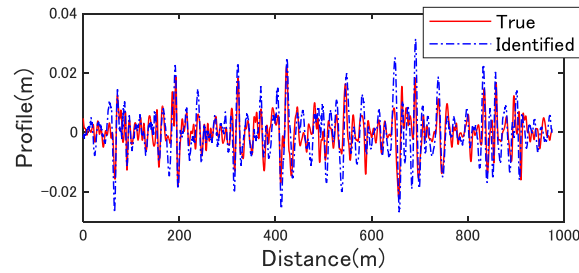


Fig. 5. Comparison of acceleration-identified and laser-measured profiles (“True” denotes the laser-measured; “Identified” denotes the acceleration-identified).

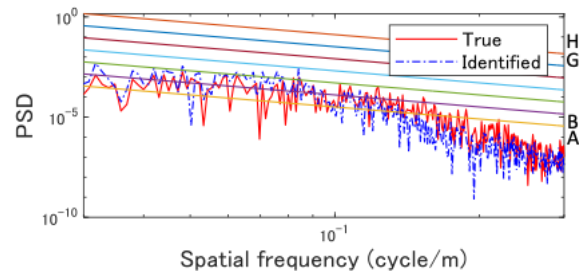


Fig. 6. PSDs of acceleration-identified and laser-measured profiles (“True” denotes the laser-measured; “Identified” denotes the acceleration-identified).

the accumulated vertical displacement of the vehicle to the distance traveled when a 2-DOF quarter-car model runs in a numerical simulation at 80 km/h on a target roadway profile.

IRIs estimated using acceleration-identified and laser-measured profiles shown in Fig. 5 are shown in Fig. 7. IRIs are calculated at a regular interval of 0.1m for the 200m segments. The absolute IRI values in Fig. 7 show a discrepancy between the acceleration-identified profile and the laser-measured profile. The acceleration-identified IRI is larger than the laser-measured IRI. However, the trend of IRI is similar in almost all areas in the target roadway.

One of the major sources of the difference in IRI is that the laser-measured profile and the acceleration-identified profile are slightly different variables. The laser-measured profile is measured using three laser displacement transducers with a technique called the three-point method²²⁾, which does not include large bridge vibration components. Due to the nature of the method, the long-wavelength component of the roadway profile cannot also be measured. On the other hand, the acceleration-identified profile strictly includes the displacement due to bridge vibration in addition to the roadway profile in the identification results, and relatively long-wavelength components can be identified. Therefore, the IRI from acceleration-identified profiles may contain a long-wave component with a larger amplitude than that of short-wave components.

Other possible sources of the difference are rooted in insufficiency of estimated vehicle properties, improper selection of cut-off frequencies of the bandpass filter applied to the identified roadway profile, and errors related to vehicle modeling. Among these sources of difference, the vehicle properties can be improved by obtaining accurate values through detailed free vibration experiments. Modeling errors can be addressed by changing to a more advanced model. Selecting appropriate cut-off frequencies of the bandpass filter can also be optimized by prior studies so as to obtain higher identification accuracy of IRI. However, it is difficult to directly solve the problem of the theoretical difference between the acceleration-identified and laser-measured profiles. This is because it is difficult to accurately separate the bridge vibration component from the roadway profile component in the acceleration-identified profile without any additional input. Therefore, for the purpose of estimating IRI, this study proposes a method to correct the estimated IRI by applying a correction factor, which is a future task. By introducing

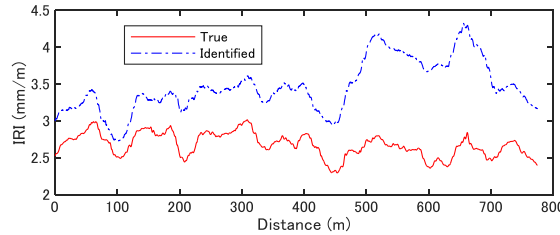


Fig. 7. IRIs of acceleration-identified and laser-measured profiles (“True” denotes the laser-measured; “Identified” denotes the acceleration-identified).

such a correction factor, it is possible to easily calibrate some error sources such as vehicle specification errors and bandpass filter problems together.

4 Conclusion

In this study, the validity of the roadway roughness profile identification by dynamic regularized least square minimization method using vehicle acceleration was verified with a field experiment conducted on a highway by driving at about 70 km/h. Major observations of the study are summarized as follows.

- 1) The acceleration-identified profile matched well with the laser-measured profile.
- 2) The PSD of the acceleration-identified profile was also comparable with the laser-measured profiles.
- 3) The absolute IRI value obtained from the acceleration-identified profile resulted in lower accuracy. However, using the IRI relative to the reference may provide sufficient accuracy, and therefore is a topic for future work.

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